

EBAC-DCC Analysis of World Data of πN , γN , and $N(e, e')$ Reactions

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Abstract. The development, results, and prospect of the Dynamical Coupled-Channels analysis at Excited Baryon Analysis Center (EBAC-DCC) are reported.

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INTRODUCTION

The Excited Baryon Analysis Center (EBAC) at Jefferson Lab was established in the Spring of 2006 for investigating the nucleon resonances (N^*). In this contribution, we report on the development, results, and prospect of EBAC.

The EBAC project has three components, as illustrated in Fig. 1. The first task is to perform a dynamical coupled-channels analysis of the *world* data of πN , $\gamma^* N \rightarrow \pi N$, ηN , $\pi\pi N$, $K\Lambda$, $K\Sigma$, ωN , \dots to determine the meson-baryon partial-wave amplitudes. The second step is to develop a procedure to extract the N^* parameters from the determined partial-wave amplitudes. The third step is to investigate the interpretations of the extracted N^* properties in terms of the available hadron models and Lattice QCD.

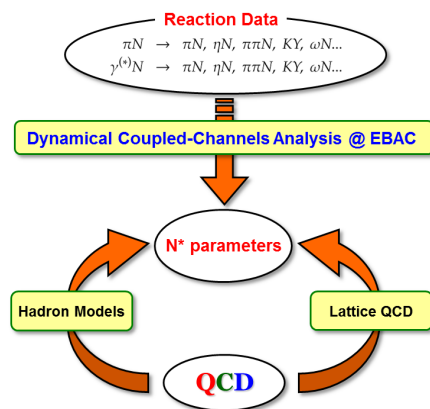


FIGURE 1. The strategy of the EBAC project.

EBAC-DCC MODEL

The EBAC analysis is based on a Hamiltonian formulation [1] within which the reaction amplitudes $T_{\alpha,\beta}(p, p'; E)$ in each partial-wave are calculated from the following coupled-channels integral equations,

$$T_{\alpha,\beta}(p, p'; E) = V_{\alpha,\beta}(p, p') + \sum_{\gamma} \int_0^{\infty} q^2 dq V_{\alpha,\gamma}(p, q) G_{\gamma}(q, E) T_{\gamma,\beta}(q, p', E), \quad (1)$$

$$V_{\alpha,\beta} = v_{\alpha,\beta} + \sum_{N^*} \frac{\Gamma_{N^*,\alpha}^{\dagger} \Gamma_{N^*,\beta}}{E - M^*}, \quad (2)$$

where $\alpha, \beta, \gamma = \gamma N, \pi N, \eta N, KY, \omega N$, and $\pi\pi N$ which has $\pi\Delta, \rho N, \sigma N$ resonant components, $v_{\alpha,\beta}$ are meson-exchange interactions deduced from phenomenological Lagrangian, $\Gamma_{N^*,\beta}$ describes the excitation of the nucleon to a bare N^* state with a mass M^* , and $G_{\gamma}(q, E)$ is a meson-baryon propagator. The EBAC-DCC model, defined by Eqs. (1) and (2), satisfies two- and three-body unitarity conditions which are the most essential theoretical requirements. Compared with the approaches based on K-matrix or dispersion-relations, the EBAC-DCC approach has one distinct feature that the analysis can provide information on reaction mechanisms for interpreting the extracted nucleon resonances in terms of the coupling of the bare N^* states with the meson clouds generated by the meson-exchange interaction $v_{\alpha,\beta}$.

DEVELOPMENT IN 2006-2010

In order to determine the parameters associated with the strong-interactions parts of $V_{\alpha,\beta}$ of Eq. (2), the EBAC-DCC model was first applied to fit the πN elastic scattering up to invariant mass $W = 2$ GeV. For simplicity, KY and ωN channels were not included during this developing stage. The electromagnetic parts of $V_{\alpha,\beta}$ were then determined by fitting the data of $\gamma p \rightarrow \pi^0 p, \pi^+ n$ and $p(e, e' \pi^{0,+}) N$.

The resulting 5-channels model was then tested by comparing the predicted $\pi N, \gamma N \rightarrow \pi\pi N$ production cross sections with the data. In parallel to analyzing the data, a procedure to analytically continue Eqs. (1) and (2) to the complex energy plane was developed to extract the positions and residues of nucleon resonances.

In the following, we present the sample results from these efforts.

Results for single pion production reactions

In fitting the πN elastic scattering, we found that one or two bare N^* states were needed in each partial wave. The coupling strengths of the $N^* \rightarrow MB$ vertex interactions $\Gamma_{N^*,MB}$ with $MB = \pi N, \eta N, \pi\Delta, \rho N, \sigma N$ were then determined in the χ^2 -fits to the data. Our results were given in Ref. [2].

Our next step was to determine the bare $\gamma N \rightarrow N^*$ interaction $\Gamma_{N^*,\gamma N}$ by fitting the $\gamma p \rightarrow \pi^0 p$ and $\gamma p \rightarrow \pi^+ n$ data. We found [3] that we were able to fit the data only up

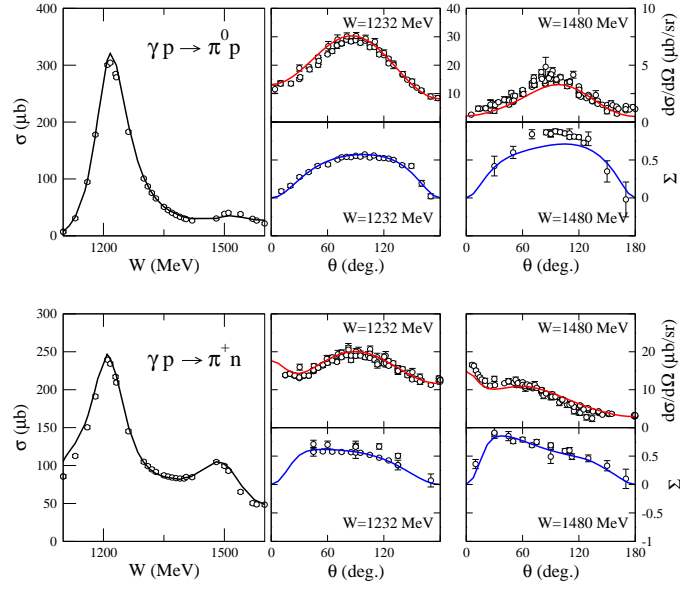


FIGURE 2. The EBAC-DCC results [3] of total cross sections (σ), differential cross sections ($d\sigma/d\Omega$), and photon asymmetry (Σ) of $\gamma p \rightarrow \pi^0 p$ (upper parts), $\gamma p \rightarrow \pi^+ n$ (lower parts).

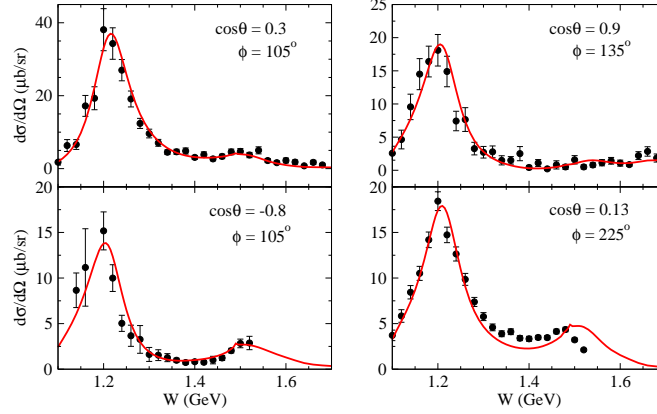


FIGURE 3. The EBAC-DCC results [4] of the differential cross sections of $p(e, e' \pi^0) p$ defined by $d\sigma/d\Omega = (\Gamma_\gamma)^{-1} d^5\sigma / (dE_{e'} d\Omega_{e'} d\Omega_\pi^*)$ with $\Gamma_\gamma = [\alpha / (2\pi Q^2)] (E_{e'} / E_e) [|\vec{q}_L| / (1 - \varepsilon)]$. $\theta \equiv \theta_\pi^*$ and $\phi \equiv \phi_\pi^*$.

to invariant mass $W = 1.6$ GeV, mainly because we did not adjust any parameter which was already fixed in the fits to πN elastic scattering. Some of our results for total cross sections (σ), differential cross sections ($d\sigma/d\Omega$), and photon asymmetry (Σ) are shown in Fig. 2.

The Q^2 -dependence of the $\Gamma_{N^*, \gamma N}$ vertex functions were then determined [4] by fitting the $p(e, e' \pi^0) p$ and $p(e, e' \pi^+) n$ data up to $W = 1.6$ GeV and $Q^2 = 1.5$ (GeV/c) 2 . Here we also did not adjust any parameter which was already fixed in the fits to πN elastic scattering. In Fig. 3 we show four of our fits.

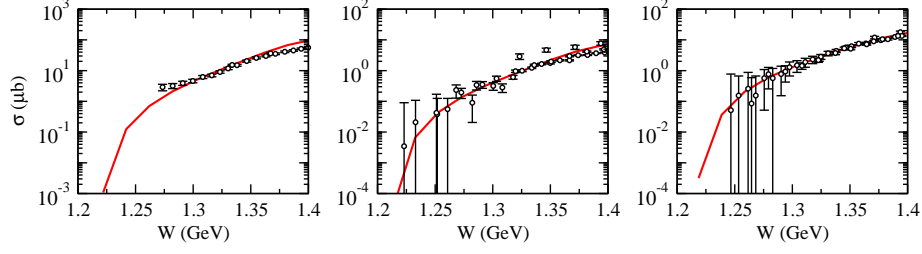


FIGURE 4. The predicted [6] total cross sections of $\gamma p \rightarrow \pi^+ \pi^0 n$ (left), $\pi^0 \pi^0 p$ (center), $\pi^+ \pi^- p$ (right) are compared with the data at $W \leq 1.4$ GeV.

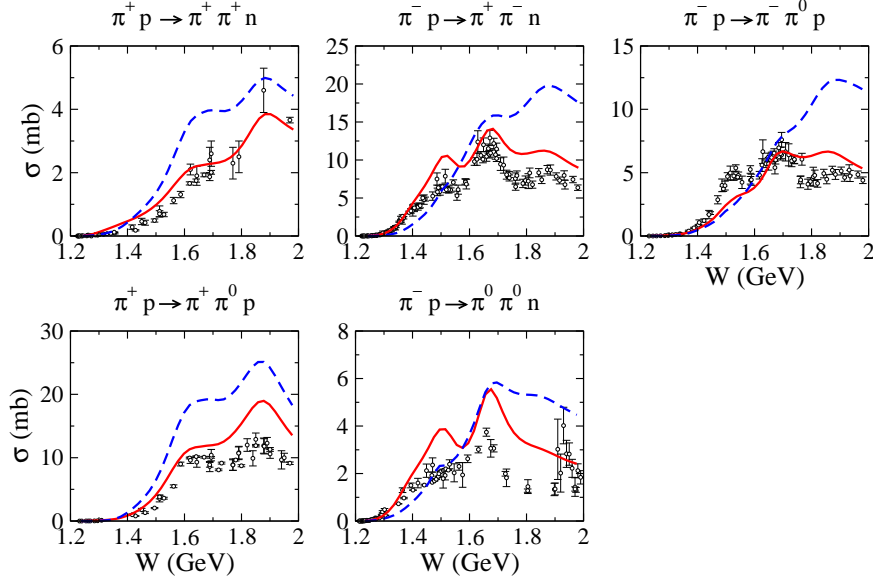


FIGURE 5. The predicted [5] total cross sections of $\pi N \rightarrow \pi \pi N$ are compared with the data. The dashed-curves are obtained when the coupled-channel effects are turned off within the EBAC-DCC model.

Results for two-pions production reactions

The model constructed from fitting the data of single pion production reactions was then tested by examining the extent to which the $\pi N \rightarrow \pi \pi N$ and $\gamma N \rightarrow \pi \pi N$ data can be described. It was found [5, 6] that the predicted total cross sections are in excellent agreement with the data in the near threshold $W \leq 1.4$ GeV. Our results for $\gamma p \rightarrow \pi^+ \pi^- p, \pi^+ \pi^0 n, \pi^0 \pi^0 p$ are shown in Fig. 4. In the higher W region, the predicted $\pi N \rightarrow \pi \pi N$ cross sections can describe to a very large extent the available data, as shown in Fig. 5. Here the important role of the coupled-channel effects were also demonstrated. However, the predicted $\gamma p \rightarrow \pi^+ \pi^- p, \pi^0 \pi^0 p$ cross sections were a factor of about 2 larger than the data while the shapes of two-particles invariant mass distributions could be described very well.

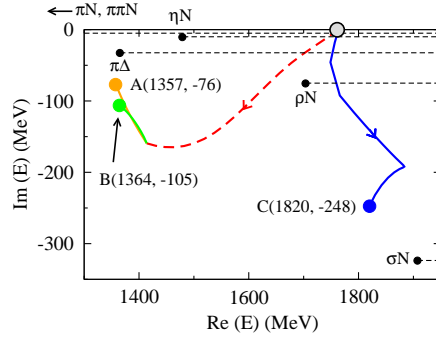


FIGURE 6. The trajectories of the evolution of three nucleon resonances in P_{11} from the same bare N^* state. The results were from Ref. [9].

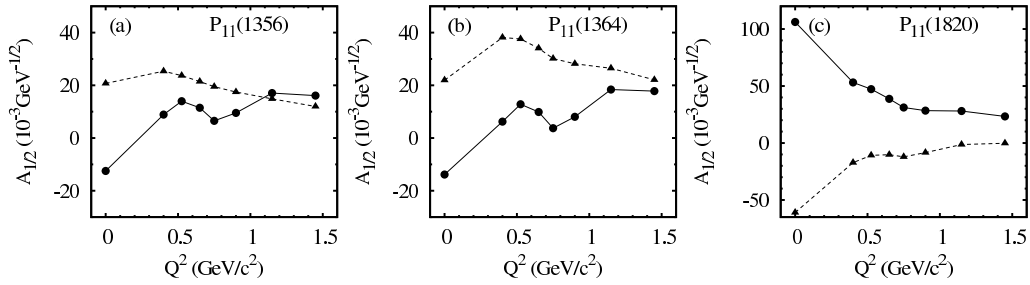


FIGURE 7. The extracted [8] $\gamma N \rightarrow N^*$ form factors for the first three P_{11} nucleon resonances. Solid (dashed) curves are their real (imaginary) parts.

Resonance Extractions

We follow the earlier works, as reviewed and explained in Refs. [7, 8], to define that the resonances are the eigenstates of the Hamiltonian with only outgoing waves of their decay channels. One then can show that the nucleon resonance positions are the poles M_R of meson-baryon scattering amplitudes calculated from Eqs. (1) and (2) on the unphysical sheets of complex- E Riemann surface. The coupling of meson-baryon states with the resonances can be determined by the residues $R_{N^*,MB}$ at the pole positions. Our procedures for determining M_R and $R_{N^*,MB}$ and the results were presented in Refs. [7, 8, 9, 10].

With our analytic continuation method [7, 8], we were able to analyze the dynamical origins of the nucleon resonances extracted from the EBAC-DCC model. This was done by examining how the resonance positions move as the coupled-channels effects are gradually turned off. As illustrated in Fig. 6 for the P_{11} states, this exercise revealed that the two poles in Roper region and the next higher pole are associated with the same bare state.

The extracted residues $R_{N^*,MB}$ are complex which is the necessary mathematical consequences of any approach based on a Hamiltonian formulation. As an example, the extracted $N^* \rightarrow \gamma N$ form factors for the three P_{11} resonances indicated in Fig. 6 are shown in Fig. 7. To complete the EBAC project, we must investigate how these results can be related to the current hadron models and Lattice QCD.

PROSPECT

During the developing stage of EBAC in 2006-2010, the EBAC-DCC model parameters were determined by analyzing separately the following data: $\pi N \rightarrow \pi N$ [2], $\gamma N \rightarrow \pi N$ [3], $N(e, e'\pi)N$ [4], $\pi N \rightarrow \pi\pi N$ [5], and $\gamma N \rightarrow \pi\pi N$ [6]. The very extensive data of $K\Lambda$ and $K\Sigma$ production were not included in the analysis. To have a high precision extraction of nucleon resonances, it is necessary to perform a *combined* simultaneous coupled-channels analysis of all meson production reactions.

We have started the first combined analysis of *world* data of $\pi N, \gamma N \rightarrow \pi N, \eta N, K\Lambda, K\Sigma$ since the summer of 2010. Preliminary results have been obtained. We expect to complete this task in the Spring of 2012.

The combined analysis must be continued to also fit the *world* data of meson electroproduction data for extracting $\gamma N \rightarrow N^*$ form factors up to sufficiently high Q^2 . In addition, we should explore the interpretations of the extracted resonance parameters in terms of Lattice QCD and the available hadron models, such as the Dyson-Schwinger-Equation model and constituent quark model. This last step is needed to complete the EBAC project with conclusive results, as indicated in Fig. 1.

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REFERENCES

1. A. Matsuyama, T. Sato, and T.-S. H. Lee, *Phys. Rept.* **439**, 193–253 (2007).
2. B. Juliá-Díaz, T.-S. H. Lee, A. Matsuyama, and T. Sato, *Phys. Rev. C* **76**, 065201 (2007).
3. B. Juliá-Díaz, T.-S. H. Lee, A. Matsuyama, T. Sato, and L. C. Smith, *Phys. Rev. C* **77**, 045205 (2008).
4. B. Juliá-Díaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, T. Sato, and N. Suzuki, *Phys. Rev. C* **80**, 025207 (2009).
5. H. Kamano, B. Juliá-Díaz, T.-S. H. Lee, A. Matsuyama, and T. Sato, *Phys. Rev. C* **79**, 025206 (2009).
6. H. Kamano, B. Juliá-Díaz, T.-S. H. Lee, A. Matsuyama, and T. Sato, *Phys. Rev. C* **80**, 065203 (2009).
7. N. Suzuki, T. Sato, and T.-S. H. Lee, *Phys. Rev. C* **79**, 025205 (2009).
8. N. Suzuki, T. Sato, and T.-S. H. Lee, *Phys. Rev. C* **82**, 045206 (2010).
9. N. Suzuki, B. Juliá-Díaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, and T. Sato, *Phys. Rev. Lett.* **104**, 042302 (2010).
10. H. Kamano, S. X. Nakamura, T.-S. H. Lee, and T. Sato, *Phys. Rev. C* **81**, 065207 (2010).